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EVALUATION OF DIGITAL CORRECTION TECHNIQUES FOR ERTS IMAGES

March, 1973

Interim Report for Period September, 1972 - February, 1973

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16. Abstract

This document reports on the progress attained during the first six months of activity under Contract No. NAS5-21814 from September, 1972 through February, 1973. The purpose of the contract is to demonstrate precision geometric and radiometric correction of bulk digital ERTS imagery by digital methods, and to evaluate the techniques utilized from the point of view of precision and speed. Included in this report are brief descriptions of the processing methods applied to ERTS imagery, examples of imagery so far processed and a description of the program for the next report interval (March-April, 1973). To date, the principal items of software required to correct bulk digital image tapes have either been developed, or adapted from previously extant software for the ERTS requirements. MSS imagery have been processed by means of this software with good results. Error analyses of the performance of a Kalman filter used with Ground Control Points have also been performed.

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PREFACE

This document reports on the progress attained during the first six months of activity under Contract No. NAS5-21814 from September, 1972 through February, 1973. The purpose of the contract is to demonstrate precision geometric and radiometric correction of bulk digital ERTS imagery by digital methods, and to evaluate the techniques utilized from the point of view of precision and speed. Included in this report are brief descriptions of the processing methods applied to ERTS imagery, examples of imagery so far processed and a description of the program for the next reporting interval (March-April, 1973). To date, the principal items of software required to correct bulk digital image tapes have either been developed, or adapted from previously extant software for the ERTS requirements. MSS imagery have been processed by means of this software with good results. A Data Analysis Plan will shortly be submitted to NASA describing the analyses to be undertaken during the final phase (Phase III) of this contract.

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1.0 INTRODUCTION

This document summarizes key results attained during the first six months under contract. Also presented is an outline of the processing techniques employed including, in particular, the resampling technique for geometric and photometric correction of imagery. Examples of MSS imagery processed by these methods are illustrated here, and were contained in a paper presented at the Symposium on Significant Results Obtained from ERTS-1, March 5-9, 1973. Processing times have been demonstrated to be comparable to tape read/write times. Error analyses of the performance of a Kalman filter used with Ground Control Points (GCP's) have also been performed.

Section 2 reviews the achievements of the first four months of the contract, and which were reported on earlier. This section also contains a brief description of the processing approach taken by TRW. Section 3 reports on progress during the past two months, and contains examples of the first results. Section 4 describes the activities planned for the next two months, and Section 5 summarizes conclusions of the study to date.

2.0 REVIEW OF ACTIVITY: September-December, 1972

2.1 Approach

In order to understand the significance of the results described below, it would be useful to describe the approach TRW has taken to the problem of digitally correcting ERTS images. A schematic diagram of the MSS software* is given in Figure 2-1. It may be seen that two processing passes of the image data are required in this approach: (1) first the bulk data tapes are reformatted to produce a single band/scene on individual files of data on a Computer Compatible Tape (CCT); (2) the reformatted image data is processed by means of a "resampling" algorithm, which combines both geometric correction (rectification) and radiometric (intensity) correction in a single step. The necessary parameters for this resampling operation are derived during the first pass processing (during which the bulk tapes are reformatted) utilizing annotation tape data (attitude, ephemeris) alone, or in combination with GCP attitude refinement.

The attitude refinement is accomplished by means of a Kalman filter which accepts GCP location data and attitude/ephemeris data as inputs and produces refined attitude outputs. Either the refined attitude resulting from GCP processing or the initial attitude data alone are input to a distortion coefficient calculation code, which generates the coefficients which are input to the second pass program. The distortion coefficients define the amounts by which the bulk image must be "distorted" so as to produce a rectified image, i.e., one which is linear in meter/meter coordinates.

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* The RBV software is functionally very similar, and thus it will not be necessary to discuss it any further at this time. The principal difference is the additional requirement for reseau identification, which is accomplished by means of a shadow casting technique.

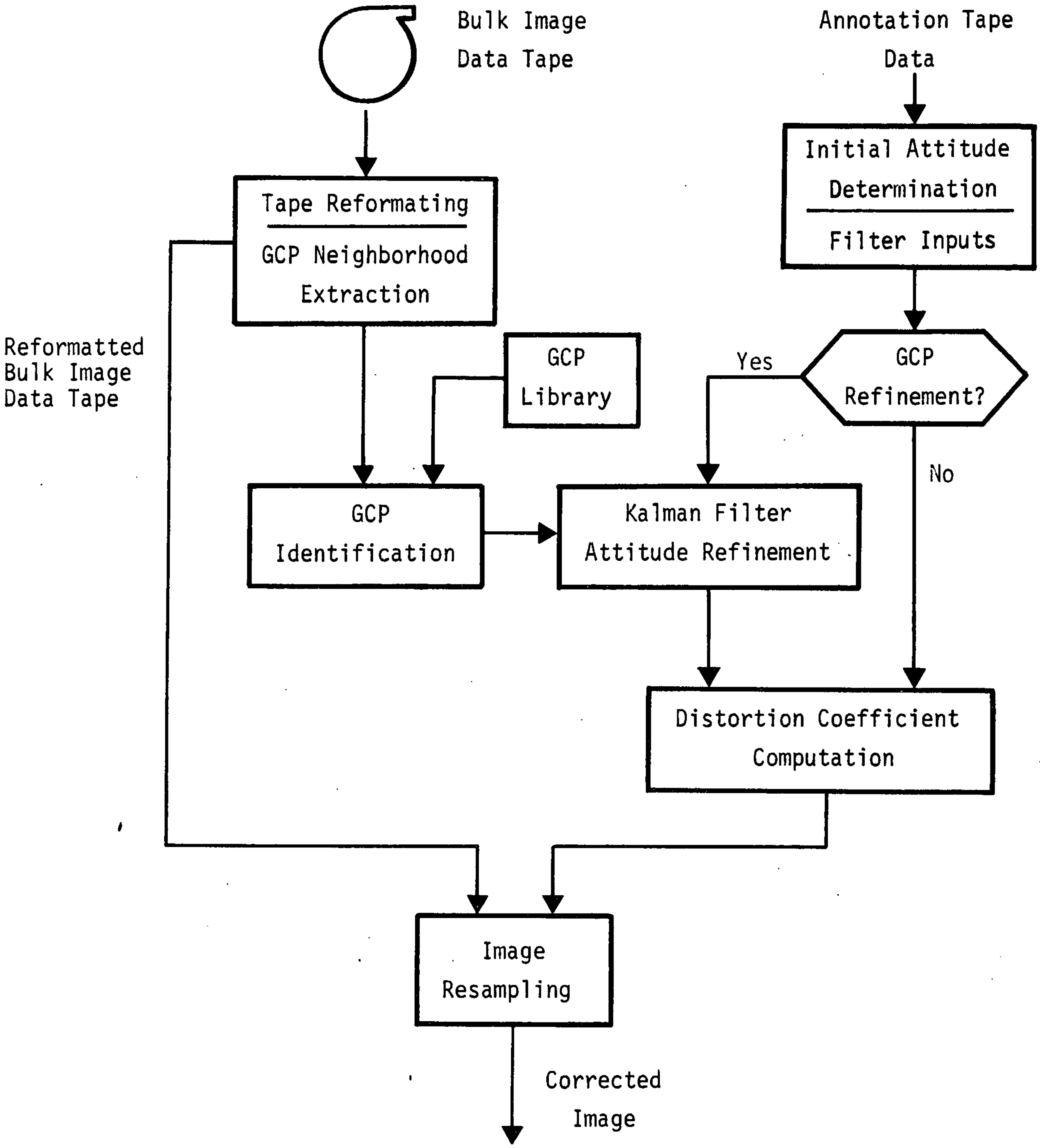


Figure 2-1. Precision Correction Software Schematic

The computation of the second pass distortion coefficients is accomplished by mapping a small number of image locations (lines/pixels) called "pseudo reseaux" to the desired meter/meter coordinate system. To do this it is necessary to include the effects of mirror scan, spacecraft attitude, velocity and altitude, sensor pointing error, earth rotation and earth curvature. Utilizing the mapping between input (bulk) and output (final) image coordinate systems, distortion coefficients are defined for each block of four pseudo reseaux so as to map the input image to the desired rectified coordinate system. A piecewise bilinear spatial distortion model is used, of the form

$$\delta_x = a_0 + a_1 x + a_2 y + a_3 xy$$

$$\delta_y = b_0 + b_1 x + b_2 y + b_3 xy$$

where δ_x and δ_y are the respective distortions in the output image x and y directions, respectively. It has been shown at TRW that for a sufficient density of pseudo reseaux, the errors associated with using a bilinear distortion model can be made arbitrarily small. In particular, a reasonable number of pseudo reseaux (less than 100 for an entire image) will produce model errors less than the self-consistency errors (all other errors associated with the mirror scan, ephemeris and attitude, etc.).

All of the calculations just outlined are straightforward and can be accomplished very quickly ($\sim$ 5 sec CPU for an entire image), with the possible exception of the GCP identification. One standard method is to cross correlate chosen subareas of the bulk image against a reference template image. Typical times for a subarea 120 pixels x 120 lines and a template $\sim$ 30 pixels x 30 lines are $\sim$ 10 sec. TRW will examine and evaluate alternative algorithms in the course of the remainder of this contract which offer significant improvements in running time.

The more time consuming part of the processing is the second pass image "resampling." Conceptually, this operation consists of reconstructing in its entirety the corrected (rectified) image and then sampling its intensity values at predesignated positions (lines/pixels) within the image. It should be clearly understood that at no time is the input image data physically distorted, with data values subsequently defined by interpolation. The power of the resampling method becomes clear when it is realized that complete flexibility is afforded in the matter of pixel spacings and line spacings (independently), thus making possible the custom tailoring of the corrected image to any application and/or hardware constraints.

The resampling method is implemented by means of a convolution algorithm. Ideal one-dimensional resampling of band-limited digital data is of the form

$$I(x_i) = \sum_{x_k} I(x_k) f(x_i - x_k),$$

wherein $f(x)$ is of the form $\sin x/x$, x_i is the argument (pixel location) chosen for the resampled function I, and the set of x_k is the set of arguments of the available digital data $I(x_k)$, that is, the bulk data values. TRW has approximated this ideal $\sin x/x$ resampling by means of a continuous symmetric cubic polynomial function, possessing a continuous first derivative and vanishing beyond $\pm$ 2 pixels (lines). Subject to these and a few other constraints, a unique function results, as shown in Figure 2-2. For obvious reasons it is called the "cubic convolution function." It was shown in the TRW proposal leading to the current contract that cubic convolution results in very small errors compared to other methods for generating $I(x_i)$. These other methods for obtaining the value of a function at a point given values of the function at nearby points is called interpolation, and is illustrated in Figure 2-3 for nearest neighbor and bilinear interpolation.

Nearest neighbor interpolation involves choosing the value of the pixel closest to the desired pixel location as the interpolated value, as shown in Figure 2-3-a. Only one pixel value of the bulk image is

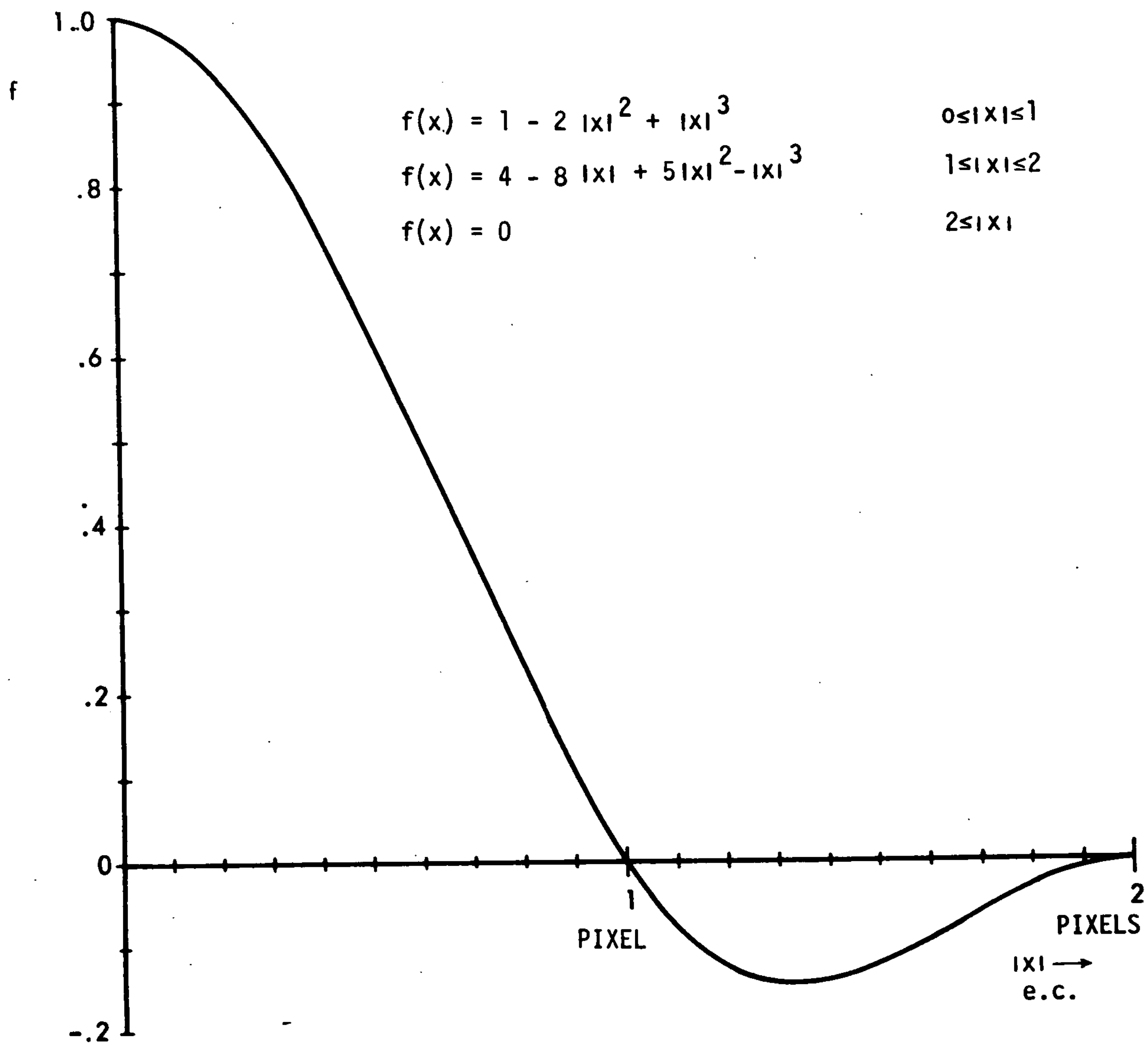
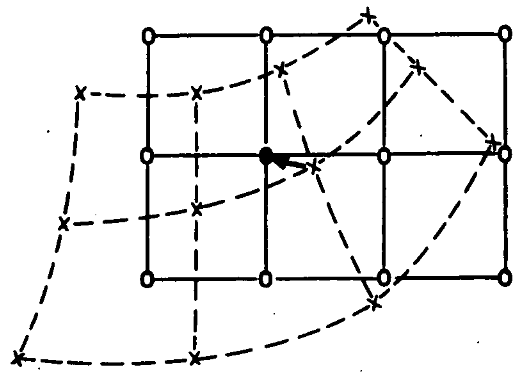
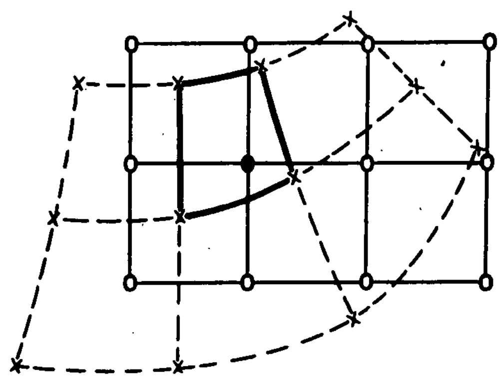


Figure 2-2. **Cubic Convolution Interpolation Function**



(a) Nearest Neighbor Interpolation



(b) Bilinear Interpolation

Figure 2-3. Two Possible Interpolation Algorithms. Circles denote uniform pixel locations in the output, corrected image. x's denote the irregular grid of pixels (in the corrected image), derived by straightforward corrective distortions to the input bulk image. Filled-in zero is a typical pixel, the value of which is to be interpolated.

required for each interpolated value, and only original values are used. The algorithm is thus very fast. Note however, that errors accumulate in finite ($\pm$ 1/2 pixel) increments and thus will result in 1 pixel offsets throughout the corrected image.

Bilinear interpolation, shown in Figure 2-3-b, utilizes a bilinear combination of the four closest pixel values to produce a new, interpolated pixel value. The smoothing effects of bilinear interpolation preclude the one pixel offsets characteristic of nearest neighbor interpolation. By the same token, this smoothing effect can cause a small amount of image degradation. Also, the algorithm is inherently slower, inasmuch as a new pixel value must be computed from four other values.

In contrast to nearest neighbor and bilinear interpolation, cubic convolution resampling requires the values in a grid 4 pixels x 4 lines about the point at which the interpolated value is desired. Thus, both slope and continuity properties of the function to be resampled are preserved (and expected on the basis of its approximation to ideal sinx/x resampling). As a consequence, high resolution with minimum distortion is anticipated, with some penalty in CPU time compared to bilinear interpolation. It will be seen in Section 3, however, that quite acceptable CPU times have been attained with TRW's implementation of cubic convolution resampling.

2.2 Achievements

During the first two months of the contract, September-October, 1972, simulated data was used to exercise components of the RBV software and MSS software. No imagery tapes were received during the period, and the first system corrected images from our selected test sites became available the last week of the period.

During November-December, 1972, the first ERTS image tapes were received. GCP extraction from an ERTS scene was tested, and a Kalman filter for precision attitude determination was adapted for the ERTS application and tested against simulated data. An annotation tape became available during this period and was successfully utilized with the software for the computation of spacecraft attitude and ephemeris. The second pass resampling program was adapted to ERTS requirements, and tests using it with ERTS data were initiated.

Some appreciation for the performance of the Kalman filter in refining attitude may be gained with reference to Figures 2-4 and 2-5. The first figure shows the standard deviation in equivalent degrees for terms in the pitch state vector, as a function of the number of GCP's processed. The pitch state vector ($\dot{P}_0$, $\ddot{P}_0$, $\dddot{P}_0$) corresponds to a cubic polynomial of the form:

$$P = P_0 + \dot{P}_0 t + \frac{\ddot{P}_0}{2!} t^2 + \frac{\dddot{P}_0}{3!} t^3 \quad \text{(degrees)},$$

which is fit to annotation tape data. The standard deviations of the pitch rate, pitch acceleration and pitch rate of acceleration have been normalized to the same value to facilitate comparisons. Figure 2-5 shows a corresponding plot for the yaw state vector.

It may be seen that the zero-order pitch term is better estimated than the zero-order yaw term. This is due to the greater sensitivity of the GCP error terms (input to the filter) to pitch than to yaw deviations and can be demonstrated in a straightforward manner from geometrical considerations.

The results presented here were generated from simulated data, using a particular pattern of GCP locations. Filter performance is somewhat dependent upon GCP locations; better performance is obtained when the points are not clustered. Also, important inputs to the filter are the covariance matrix for the pitch, roll and yaw state vectors. In lieu of any measurement data, TRW has estimated these values from attitude data supplied by NASA.

B

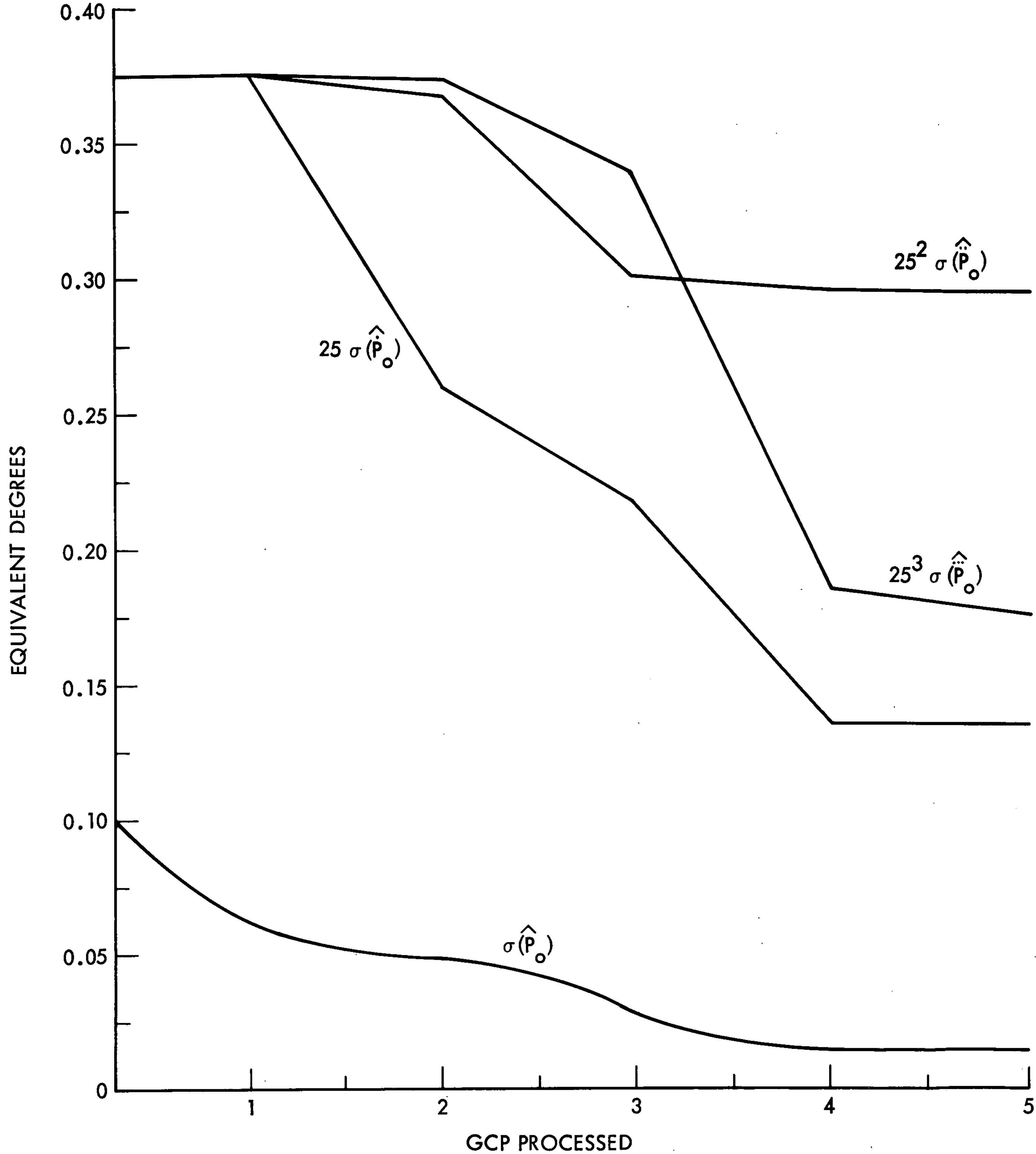


Figure 2-4. Standard Deviations in Equivalent Degrees for the Pitch State Vector (P_o, $\dot{P}_o$, $\ddot{P}_o$, $\dddot{P}_o$) Estimated at Five GCP Updates.

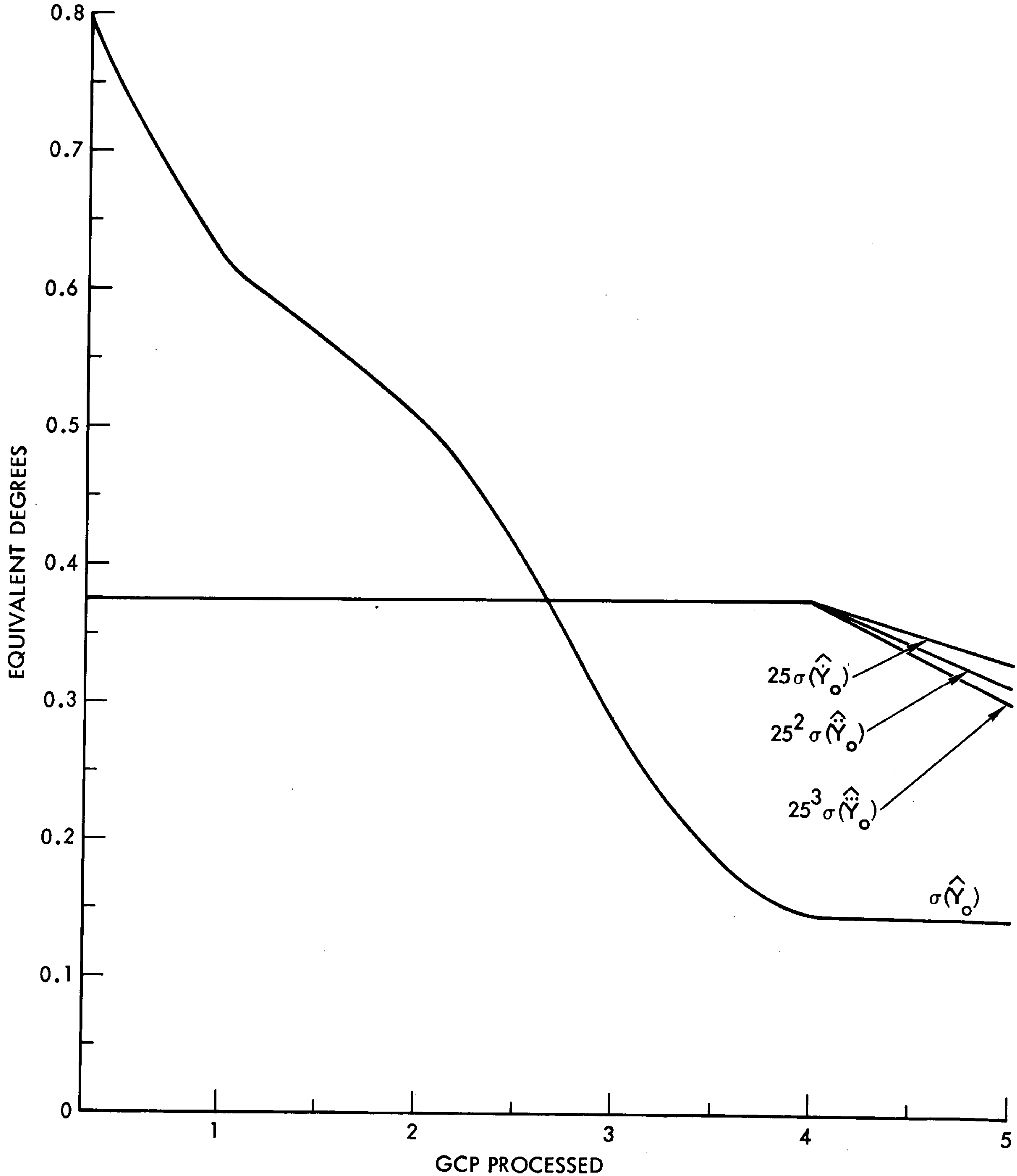


Figure 2-5. Standard Deviation in Equivalent Degrees for the YAW State Vector (Y_o, $\dot{Y}_o$, $\ddot{Y}_o$, $\dddot{Y}_o$) Estimated at Five GCP Updates.

2.3 Problems

During the first reporting interval the chief problem was lack of data and imagery. Lack of annotation tape (BIAT or DIAT) data constituted the chief difficulty during the second reporting period. Also, the Monterey Bay scene was added to our previous list of sites, with attendent delays in obtaining imagery and tapes. Mirror scan calibration data and the MSS line length adjustment algorithm similarly were not available during this interval. The lack of such data does not significantly impede progress, but will impact the quality of the final images produced.

3.0 ACTIVITY:
January-February, 1973

3.1 Achievements

By the middle of this reporting period, annotation data had been received for a scene containing San Francisco Bay and Monterey Bay and for which system corrected imagery and bulk digital data tapes had been received earlier. The first image corrected by TRW was scene 1057-18172-7. This infrared band was chosen specifically to bring out clearly the comparative effects of nearest neighbor interpolation, bilinear interpolation and cubic convolution resampling in high contrast regions of the image, i.e., land/water interfaces.

Figure 3-1 is a reproduction of the system corrected image for the entire scene supplied by NASA/GSFC. Note that this image has been corrected for the unequal number of lines (2340) and samples/line ($\sim$ 3240) in the bulk data, as well as earth rotation (which produces the $\sim$3° skew). The image has also been contrast enhanced by NASA.

Figure 3-2* shows a detail taken from the upper left corner of the same image, reconstructed** from the unrectified bulk image data tape supplied by NASA. The area shown is approximately 45 Km across and 50 Km down.

A rectified image corresponding to the detail in Figure 3-2 is given in Figure 3-3, utilizing the nearest neighbor interpolation algorithm and without precision GCP attitude refinement. The area shown is 46.25 Km x 36.4 Km, and is aligned parallel to the spacecraft ground track. Note the steps occurring on the left edge of the image, cor-

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* The pictures included here have been slightly contrast enhanced so as to bring out the image detail more clearly. The photometrically corrected data is, of course, preserved on the digital output tape.

** The reconstructed images were produced from the corrected image tapes by photographing directly a high resolution CRT face, at the Jet Propulsion Laboratory's Image Processing Laboratory. The bright area in the upper left corner is a result of the reconstruction process, and is not in the corrected image data.

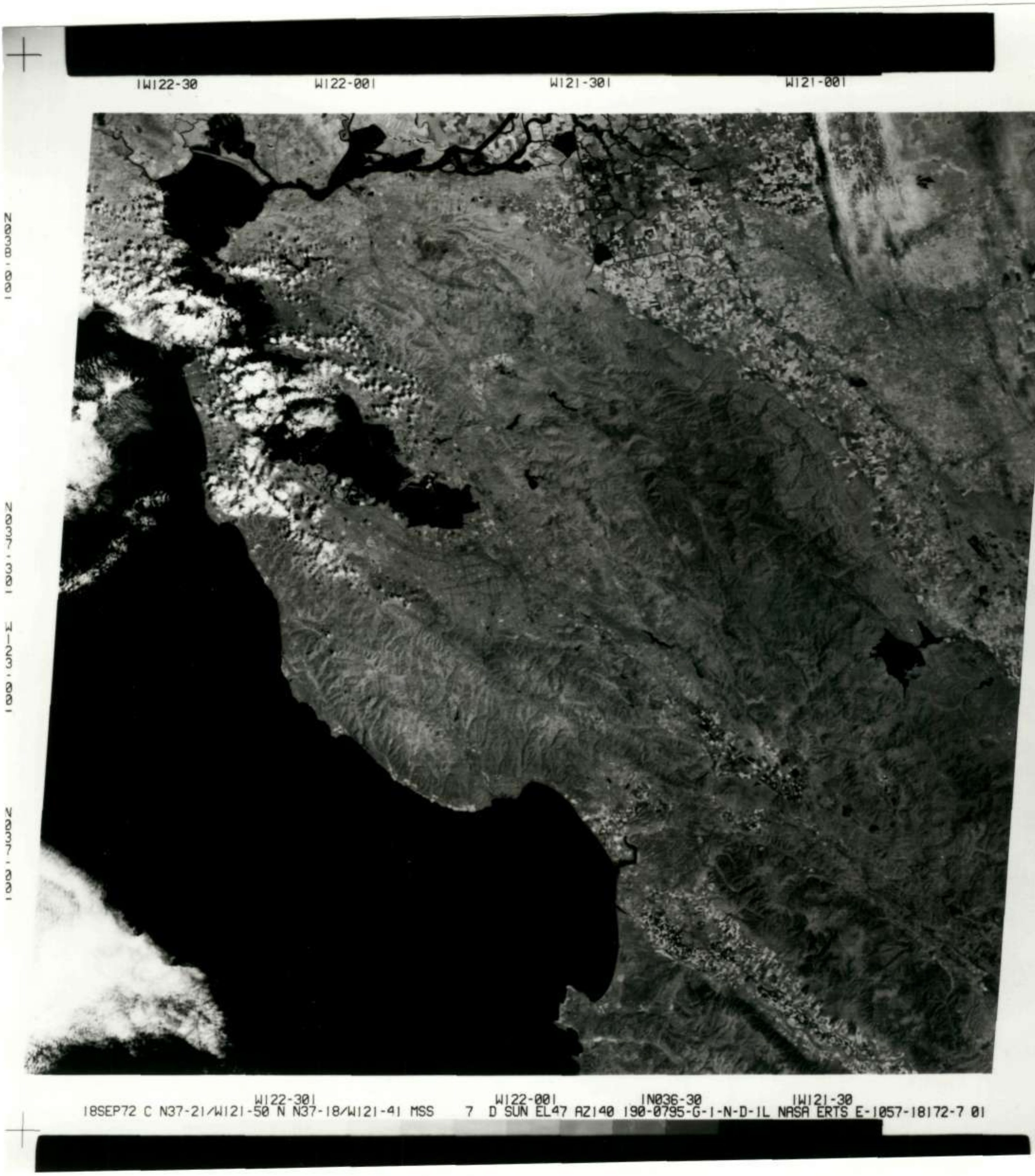

Figure 3-1. Reproduction of Scene 1057-18172-7 Bulk Image Print. The image has been corrected for the difference in the number of pixels/line and the number of lines, and has also been corrected for earth rotation (skew).

Figure 3-2. Reconstruction of Bulk Image Tape. This detail is taken from the upper left corner of Figure 3-1, and shows San Pablo Bay in the middle.

Figure 3-3. Reconstruction of a Portion of Figure 3-2 After Rectification, Using Nearest Neighbor Interpolation. Note the one pixel offsets on the left edge of the rectified image.

responding to the successive one pixel increments associated with nearest neighbor interpolation. Careful examination of the image reveals a number of areas for which this pixel jitter is observed, and which is particularly evident for such high contrast regions as those containing a boundary between land and water. Thus, for example, note the bends in the San Antonio Creek, leading off from the WNW corner of San Pablo Bay, located in the upper middle of Figure 3-3.

Figure 3-4 shows the same scene as Figure 3-3, but using bilinear interpolation instead of nearest neighbor interpolation. Note the straight line appearance of the left edge of the image, in contrast to Figure 3-3. Note also that the bends in the San Antonio Creek are cleaner. On the other hand, note the slight resolution degradation for the complex of roads (including Interstate 80) north of Carquinez Strait, and east of Mare Island and the Napa River, compared with Figure 3-3. This degradation is expected by virtue of the smoothing effect of bilinear interpolation, and is absent in nearest neighbor interpolation.

Figure 3-5* shows a portion of the same area resulting from the cubic convolution resampling algorithm**. Detailed comparisons between Figures 3-4 and 3-5 show a number of areas in which the resolution resulting from cubic convolution is superior to bilinear interpolation, while at the same time there is no evidence of the pixel offsets associated with nearest neighbor interpolation.

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* In order to obtain this picture, a non-standard development process was utilized, compared to Figures 3-2 through 3-4. The resulting contrast was very poor, and could not be entirely compensated for in this reproduction.

** The area shown is one-half the width of the previous examples due to a peculiarity in the processing method completely extraneous to the resampling algorithm. The corrected digital data tape for this image does not possess any such defects.

Figure 3-4. Reconstruction of a Portion of Figure 3-2 After Rectifi-Cation, Using Bilinear Interpolation. Note the smooth appearance of the left edge of the rectified image, in comparison to Figure 3-3.

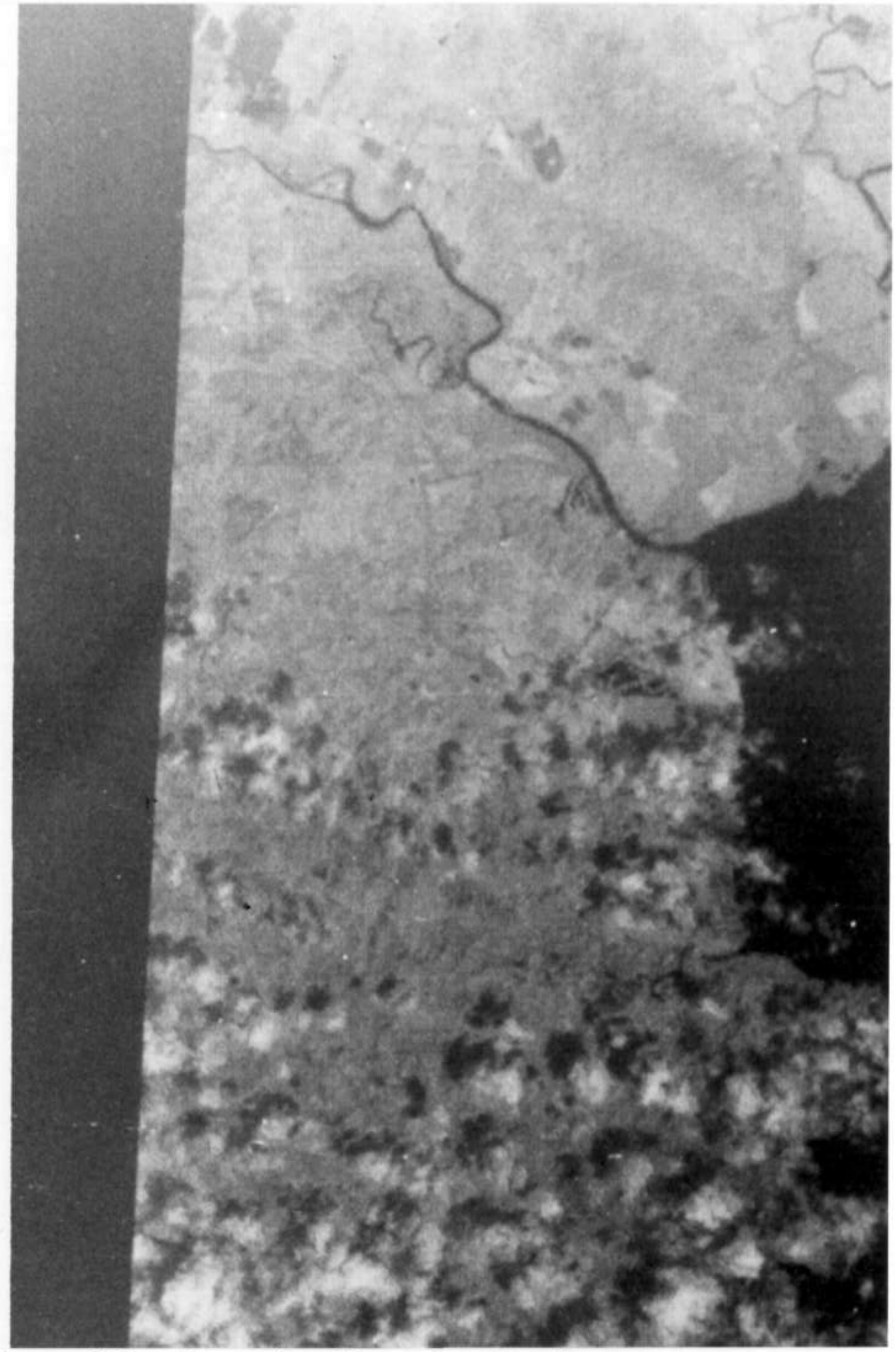

Figure 3-5. Reconstruction of a Portion of Figure 3-2 After Rectification, Using Cubic Convolution Resampling.

It is worthwhile emphasizing here that the rectification processing was accomplished by all digital processing methods, utilizing input digital imagery. In contrast to this, bulk imagery such as in Figure 3-1 is produced at the NASA Data Processing Facility by converting digital data to analogue data, and then utilizing an Electron Bean Recorder to rescan the image onto the output film.

In addition, it is useful to point out the required processing times for the production of rectified imagery. The images shown in Figures 3-3 through 3-5 were processed on a CDC 6400. Exclusive of the resampling portion, the required processing time was less than 10 seconds. Including GCP processing, the time required is of the order of a minute or two (depending on the number of GCP's). The more time consuming portion is the resampling algorithm, which requires approximately 52 seconds of CPU time per 10^6 pixels for bilinear interpolation. Cubic convolution requires approximately 110 seconds. In contrast, extrapolations to a PDP-11/45 minicomputer indicate 28 seconds of CPU (per 10^6 pixels) would be required for bilinear interpolation, or approximately 60 seconds of CPU for cubic convolution. Thus, for an output image consisting of 10^7 pixels, 10 minutes of processing time would be required for cubic convolution on the minicomputer (or less than 5 minutes for bilinear interpolation), a time comparable to that required to read a CCT or write a CCT.

3.2 ERTS-1 Symposium Participation

During the March 5-9 Symposium on Significant Results Obtained from ERTS-1, TRW presented a paper containing some of the results described above.

3.3 Problems

Difficulties continue to be experienced in receiving the annotation data, corresponding bulk digital tapes and system corrected images (for initial processing runs), in a timely manner. In addition, the current lack of an in-house image hardcopy capability is producing significant delays in some of the evaluations of image quality.

4.0 PROGRAM FOR MARCH-APRIL, 1973

During the next reporting interval, it is planned to generate a Data Analysis Plan describing activities to be performed during the final (Phase III) portion of this contract. GCP refinement of the spacecraft attitude will be used for precision processing. Alternative algorithms for GCP identification will be exercised and evaluated from the point of view of speed and precision. During Phase III of the contract, RBV imagery will also be processed and statistical as well as other numerical methods will be applied to evaluate the geometric and radiometric precision of the final image products.

5.0 CONCLUSIONS

Early results have been presented for the digital rectification of ERTS imagery. Two interpolation algorithms were employed to produce the final corrected imagery included here. It was shown that small errors ($\sim$ 1 pixel, or < 60 m) result from the resampling process, for only modest CPU requirements. Nearest neighbor interpolation produces $\pm$ 1/2 pixel jitter (horizontal and vertical) which is evident in regions of high contrast. On the other hand, bilinear interpolation supplants the single pixel offsets with smooth transitions, but at the price of somewhat larger CPU times and some slight resolution degradation. The cubic convolution resampling algorithm combines the best properties of nearest neighbor and bilinear interpolation, with only modest additional CPU requirements over those for bilinear resampling.